AD-A049 117 NAVAL RESEARCH LAB WASHINGTON D C F/G 20/3

A VERSATILE SUPERCONDUCTING MAGNETOMETER/GRADIOMETER SYSTEM.(U)

OCT 77 M NISENOFF , S A WOLF

UNCLASSIFIED NRL-MR-3618 SBIE-AD-E000 046 NL

1 OF 1

AD
A049117

END
DATE
FILMED
3-78
DDC

(12)

B.S.

NRL Memorandum Report 3618

A Versatile Superconducting Magnetometer/Gradiometer System

M. NISENOFF and S. A. WOLF

Cryogenics and Superconductivity Branch
Material Sciences Division

October 1977

NAVAL RESEARCH LABORATORY
Washington, D.C.

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

(14) REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: NRL-MR-
NRL Memorandum Report 3618

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER: (9)

4. TITLE (and Subtitle): (6) A VERSATILE SUPERCONDUCTING MAGNETOMETER/GRADIOMETER SYSTEM

5. TYPE OF REPORT & PERIOD COVERED: Final Report on an NRL problem.

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s): (10) M. Nisenoff and S. A. Wolf

8. CONTRACT OR GRANT NUMBER(s): N00014-76-WR 60031

9. PERFORMING ORGANIZATION NAME AND ADDRESS:
Naval Research Laboratory
Washington, D. C. 20375

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS:
NRL Problem P05-04
RR 011-11-01
NR 319-102

11. CONTROLLING OFFICE NAME AND ADDRESS:
Office of Naval Research
Arlington, Virginia 22217

12. REPORT DATE: (11) October 1977

13. NUMBER OF PAGES: 25

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): (12) 26p.

15. SECURITY CLASS. (of this report): UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

(16) RR01111

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

(17) RR0111101

18. SUPPLEMENTARY NOTES

(18) SBIE (19) AD-E000 046

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Superconductivity
Superconductive devices
Superconducting quantum interference device
SQUID
Superconductive magnetometer
Superconductive gradiometer
Cryogenic dewar

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A versatile superconductive magnetometer/gradiometer system was designed and procured from a commerical vendor. A number of magnetic field sensing (pick-up) loops are mounted on a common substrate block and connected through a switching network to a single SQUID sensor. By suitably connecting these coils, it is possible to measure a component of the magnetic field of interest with an instrument noise level of 1.1 X 10(-14) tesla rms per root hertz or at a reduced sensitivity range with an instrument noise level of 1.3 X 10(-13) tesla rms per root hertz. In addition, (Continues)

next page

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

251 950

sub i sub i

20. Abstract (Continued)

several of the coils can be connected in opposition to measure the diagonal component of the gradient (dH_i/dx_i) of the field of interest with an instrument noise level of 1.2 × 10(-15) tesla rms per cm per hoot hertz. The dewar and probe assembly can be tilted in order to monitor either the horizontal or the vertical field component or (diagonal) gradient component of the field of interest.

CONTENTS

A VERSATILE SUPERCONDUCTING MAGNETOMETER/GRADIOMETER SYSTEM

1.0 INTRODUCTION

There is an ever increasing interest in the use of superconducting magnetometers and gradiometers in Naval surveillance and communications systems. At the present time there are on-going programs to evaluate the potential of superconductive instrumentation in the areas of Magnetic Anomaly Detection, ELF/VLF submarine communications and low frequency surveillance applications.

The Applied Superconductivity Section, Cryogenics and Superconductivity Branch, Material Sciences Division at NRL is the only Naval in-house group active in both studying the principles of operation of superconductive instrumentation and in exploring new applications opportunities for this technology in future generations of Naval electronic systems. In order to increase the effectiveness of the group to demonstrate the feasibility of using these devices in other types of low frequency systems, a versatile superconductive magnetometer/gradiometer system was acquired. This report describes the system and its performance capabilities.

2.0 BACKGROUND

There is a class of superconductive circuit elements

Note: Manuscript submitted September 19, 1977.

known by the acronym SQUID (Superconducting QUantum Interference Device) whose electrical impedance is a function of the magnitude of the changes in the ambient magnetic field to which they are exposed. These devices have been used to build vector magnetometers and gradiometers with instrument noise levels orders of magnitude smaller than that achieved by conventional systems with comparable overall physical dimensions.

The operation of a SQUID element is based on the properties of the superconducting state and, in particular, the Josephson Effect. These concepts as well as the design of systems using SQUID elements are well known and treated in detail in the literature.[1,2,3,4] In this Report, a very simplified picture of a SQUID system will be used in order to assist the reader in understanding how SQUID systems can be used to construct magnetometers and gradiometers.

A SQUID system consists of two portions, one that must be located in a cryogenic bath and the other at room temperature. The low temperature section contains the actual SQUID sensor, which must be constructed of a material which is superconducting. [Since all known superconductors have superconducting transition temperatures of the order of 23 K (-250 C) or less, a suitable cryogenic environment must be provided for this portion of the SQUID system.] In addition

to the SQUID element, there will be circuit elements such as coils, inductances, capacitors, (some made of superconducting materials while others made from normal conducting materials), and, possibly, a semi-conductor device) to provide either gain or impedance matching for the SQUID signal before it leaves the cryogenic bath. From a "systems viewpoint", the cryogenic portion of a SQUID system need only be visualized as a "black box" with two input terminals for applying the signal to be measured to the SQUID element and its associated electronic circuitry.

Connecting the cryogenic subsystem to the remainder of the system is a coaxial transmission line and, possibly, several other leads and/or transmission lines. These electrical leads must not only have low electrical losses but must also have very low thermal losses so as not to create an unreasonably large heat load on the cryogenic system. The room temperature electronics consists of various circuits to provide bias currents to the SQUID, to measure the changes in the signal from the sensor, to process this information and finally to generate a feedback signal that can be applied to the sensor so that the system is always operating at a "null". Thus the room temperature portion of a SQUID system can be visualized as another "black box" with several control knobs and an "output" terminal that provides an output voltage proportional to the

change in current at the input terminals of the cryogenic "black box" portion of the SQUID system.

Within the framework of this conceptual viewpoint, a SQUID system can be pictured as a sensitive ammeter, with input terminals at cryogenic temperatures and output terminals at room temperature. Operation of a SQUID system, in this over-simplified picture, is characterized by three parameters:

(1) the minimum value of current that can be detected (limited only by the various noise sources associated with the SQUID sensor and the conventional electronic circuit elements in the detection system

(2) the input inductance of the system (since the input circuit is typically entirely superconducting there is no resistive component to the input impedance), and

(3) a transfer function which relates a change in the output signal to a change in the input current.

In a real system, in addition to these quantities, there are various other parameters which characterize the system, such as frequency response, dynamic range, response time or "slewing rate" etc. However, for this report we will limit our attention to those parameters outlined above.

2.1 <u>Typical SQUID System Parameters</u>

The crucial parameters of the SQUID system that will

be used with the versatile magnetometer/gradiometer probe described in this report are as follows.

Minimum detectable current change = 2×10^{-11} amp rms $Hz^{-1/2}$

Input Inductance, (L_{input}) = 2 microhenries

Transfer Function $\dfrac{\Delta V_{output}}{\Delta I_{input}} = 2 \times 10^5$ Volt/amp

A more complete set of system parameters can be found in the manufacturers' literature.[5,6] However, for the preliminary design considerations to be presented in this report, these three quantities will be adequate.

2.2 Magnetometer Design Considerations

To make a component magnetometer using a SQUID system, a superconducting loop is connected to the input terminals of the SQUID system. The use of a superconducting loop results in a magnetometer system with a flat frequency response from DC to some high frequency cut-off, which is primarily determined by the characteristics of the detection electronics used with the SQUID element. (If there is finite resistance in the loop, the low frequency response will be degraded.) A change in magnetic flux, $\Delta\Phi$ linking the loop antenna of inductance L_{loop} will result in a change in current flowing through the loop antenna and the input circuit of the SQUID system, which has an input inductance of L_{input}. This change in current ΔI is given by

$$\Delta I = \frac{\Delta \Phi}{L_{loop} + L_{input}} \qquad (1)$$

For a planar loop antenna and a perpendicular ambient magnetic field, the change in magnetic flux linking the loop can be expressed as:

$$\Delta \Phi = \Delta B \cdot A \qquad (2)$$

(If the magnetic field makes an angle θ with the normal to the plane of the loop, a $\cos\theta$ factor must be included in Equation 2. However for simplicity, we will assume that $\theta=0$). Thus the minimum detectable magnetic field change for a SQUID magnetometer with a planar pickup loop of area A, and industance L_{loop} and input inductance L_{input}, is given by

$$\Delta B_{min} = \frac{L_{loop} + L_{input}}{A} \Delta I_{input,\ min.det.} \qquad (3)$$

Inspecting Eq. 3, it can be seen that ΔB_{min} can be reduced by increasing the area of the loop. In Figure I, the minimum detectable magnetic field change is plotted as a function of the radius of the loop assuming that 0.050 cm (20 mil) diameter superconducting wire is used to form the loop. For small values of loop inductance, $L_{loop}<L_{input}$, the minimum detectable field change varies inversely with the area of the pickup loop (dashed line in Figure 1). For loops with radii greater than 2.54 cm, L_{loop} is greater

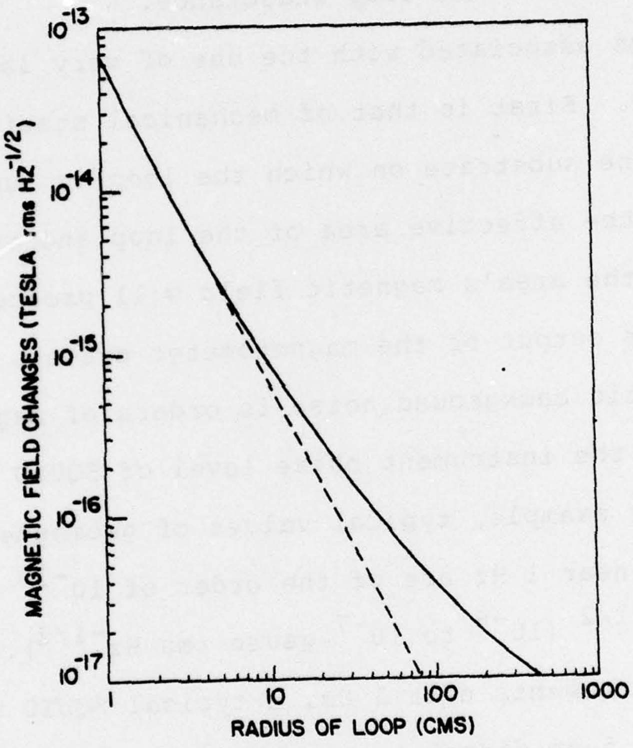

Fig. 1 — Minimum detectable magnetic field change for a SQUID magnetometer system as a function of the diameter of the magnetic field sensing coil. See text for parameters of system.

than about 0.2 microhenries and thus can no longer be neglected relative to $L_{input}=2\mu H$. The solid line in Fig. 1 was drawn taking into account explicitly the inductance of the loop. The upward deviation of this line from the dashed line of slope minus two indicates the effect of considering the finite value of the loop inductance.

Problems associated with the use of very large loops are two fold. First is that of mechanical stability. Any flexing of the substrate on which the loop is supported will change the effective area of the loop and any motion of the loop in the area's magnetic field will produce a spurious signal in the output of the magnetometer system. Secondly, the geomagnetic background noise is orders of magnitude greater than the instrument noise level of SQUID magnetometer systems. For example, typical values of geomagnetic background noise near 1 Hz are of the order of 10^{-10} to 10^{-11} tesla rms $Hz^{-1/2}$ (10^{-6} to 10^{-7} gauss rms $Hz^{-1/2}$). Thus for measurements near 1 Hz, a typical SQUID magnetometer system with a 5 cm diameter pickup loop and with a instrument noise level corresponding to 10^{-14} tesla rms $Hz^{-1/2}$ will be sensitive to magnetic field changes three to four orders of magnitude below typical background noise levels. Therefore, experience must be gained in using SQUID instruments with the present level of performance before systems with larger diameter loops and hence greater sensitivity can be usefully

employed for field studies. Once experience is gained in compensating for background noise and in providing adequate platform stability, the use of larger pickup loops, and thus increased sensitivity can be considered.

2.3 Gradiometer Design Considerations

The gradient component of the field associated with a magnetic source can be determined by measuring the magnetic field associated with the source at two points and dividing the measured field difference by the distance between the two points. In the case of a gradiometer which uses a SQUID system, the magnetic flux at two positions is measured and knowing the areas of the two loops and the separation between the two positions, the magnetic field gradient can be deduced.

To build a superconductive gradiometer, two loops of superconducting wire with "identical" areas, separated by a distance x between their centers are connected in series opposition. The terminals of the loop system are then connected (superconductively) to the input terminals of SQUID systems. The magnetic field gradient can be determined as follows:

$$\frac{\Delta B(x)}{\Delta x} = \frac{\Phi_1 - \Phi_2}{x} = \frac{B_1A_1 - B_2A_2}{x} \qquad (4)$$

Again, for convenience, it was assumed that the magnetic field is perpendicular to the planes of the loops. Assuming that $B_1 < B_2$ and that the effective areas A_1 and A_2 differ by a small

amount δA, Equation 4 can be expanded as follows:

$$\frac{B(x)}{x} = \frac{B_1 A_1 - (B_1 + \delta B)(A_1 + \delta A)}{x} = \frac{A_1}{x}\delta B + \frac{B_1}{x}\delta A + . \quad (5)$$

The first term in Equation 5 is a measure of the appropriate gradient itself; if there is no gradient in magnetic field between the two positions, the magnetic fields at the two loops are precisely equal, and there will be no net signal from the oppositely wound loops.

The second term is present even in the absence of a gradient field and thus is a undesired spurious signal. (Assume that the system is in a uniform magnetic field, as the loop system is rotated, there will be an output signal due to the second term as the orientation of B_1 relative to δA changes.) The origin of δA, can be from two sources: the normals to the loops may be precisely parallel but the physical areas may differ slightly, or the physical areas may be precisely equal but there may be a slight difference in orientation of the normals to the two loops and thus the projection of the uniform magnetic field on the normals to the two loops will be slightly different. This term in the output expressions for a gradiometer is sually referred to as the "imbalance" of the coil system. This imbalance is a nuisance as any change in the average ambient field will produce a signal in the output of the gradiometer coil system which cannot be easily distinguished from a true

gradient field signal.

There are two procedures that have been used to cancel this imbalance signal. Physically distort the loops until their effective areas have been made equal is the first. A second procedure is use small superconducting tabs positioned near one or the other loops and to distort the magnetic field lines threading the loop in order to compensate for the area inequality δA. (Note: in a general case the imbalance can be three dimensional and the trimming of the coil system must be done with this in mind.)

In specifying the performance of a superconductive gradiometer system, the degree of perfection of the coil system is commonly referred to as the "balance" of the coil system. This is an important operating parameter as it indicates how sensitive the gradiometer system is to changes in the magnitude of the ambient magnetic field. Because of the serious mechanical problem of changes in dimensions and flexing of the substrate on which the the gradiometer coils are mounted, a common practice is to specify two quantities. First, one specifies the "residual balance" of the coil system which is the degree of balance that remains after one (or many) cyclings between room and cryogenic temperatures. The other quantity is usually called simply "balance" which indicates the degree of balance that can be achieved by some trimming technique that will remain as long as the coil

system is maintained at fixed cryogenic temperature. These quantities are usually given in terms of parts per million referenced to a situation where one of the coils is (conceptually) shorted out.

2.4 Type of Gradiometers

The 3x3 matrix describing the gradient field associated with a dipole source has two types of terms, diagonal terms of the form

$$\frac{dH_i}{dx_i} \quad \text{where } i = x, y \text{ or } z$$

and off-diagonal terms of the form

$$\frac{dH_i}{dx_j} \quad \text{where } i \neq j \text{ and } i, j = x, y \text{ or } z$$

A superconducting gradiometer to measure a diagonal gradient component can be constructed by using two loops with the normals to these loops parallel and coincident. For example, such a gradiometer could be built using a cylindrical substrate and wrapping wires around the circumference of the cylinder, one at each end, and then connecting the loops in series opposition.

A superconducting gradiometer to measure another type of off-diagonal component can be built using two loops whose normals are parallel to one another but do <u>not</u> coincide. For example such an off-diagonal gradiometer could be built by mounting two coils flat on a plane surface and connecting

their leads in series opposition.

3.0 DESIGN CONSIDERATIONS

3.1 What magnetic field components need to be measured?

When acquiring a magnetic field measuring instrument, the first question that must be answered is what type of magnetic information ought to be measured. Since our objective was to acquire a fairly versatile instrument, a maximum degree of flexibility was desired. The field associated with a dipole source can be described by specifying three field components and nine gradients terms:

$$H_x \qquad H_y \qquad H_z$$

$$\frac{dH_x}{dx} \qquad \frac{dH_y}{dy} \qquad \frac{dH_z}{dz}$$

$$\frac{dH_x}{dy} \qquad \frac{dH_x}{dz} \qquad \frac{dH_y}{dx} \qquad \frac{dH_y}{dz} \qquad \frac{dH_z}{dx} \qquad \frac{dH_z}{dy}$$

However, only five of the gradient terms are independent and thus knowledge of only five gradient and three field component is required to completely specify a dipole field. Thus, at the most, only eight quantities must be measured.

After considering the funds available and the complexity of the various coil configurations, the decision was made that for a fairly versatile system to be used for preliminary "survey" work, it is probably not too restrictive to ignore the off-diagonal gradient components. This reduces the requirements to obtaining a system or systems which could measure the components of the magnetic field and the diagonal

components of the gradient field.

To completely specify a scalar field, one must measure three orthogonal components of the field. The brute force method would be to have three separate systems, loop antennas plus SQUID electronics, one with the normal to the loop antenna vertical and the other two with the normals to the loop antennas horizontal but are 90 degrees to one another. The overall system complexity can be reduced if one doesn't wish to measure all three components simultaneously. For example, one of the horizontal magnetometers is redundant as both horizontal components could be measured (at different times) by positioning the system once and then rotating the dewar (about the vertical) by 90 degrees to monitor the other horizontal component.

If there is no need for simultaneous measurements of the three components of the field, is there any way that a single magnetometer can be configured so that it can be used to monitor either the vertical component or either of the two horizontal components of the magnetic field? Traditionally, superconductive magnetometer coils are mounted in the dewar with the normal to the loop either vertical, that is parallel to the axis of the dewar, or horizontal. A standard dewar system containing such a magnetometer system is not amenable to operation with the dewar axis horizontal - liquid helium would pour out of the neck.

However, there is a way of constructing a superconductive magnetometer probe which would permit the selective measurement of either the vertical component or one of the horizontal components of the field with a single field sensing loop. Consider the situation where the magnetic field sensing loop is mounted in the dewar such that the normal to the loop is at 45 degrees to the dewar axis. With the dewar positioned with its axis vertical, the "standard" orientation, the magnetometer would be sensitive to a combination of the vertical and the (appropriate) horizontal component. However, if the dewar is tilted 45 degrees with respect to the vertical in one direction, the normal to the loop would be vertical and thus sense the z component of the ambient magnetic field, while with the dewar tilted in the other direction, the normal to the loop would be horizontal and thus either the x- or the y-component of the ambient field, or a combination of these two, would be measured. Thus, by not requiring simultaneous monitoring of the three field components, a single loop antenna and a single SQUID system is sufficient.

To monitor the diagonal components of the gradient field with a gradiometer, the same type of argument given in the previous paragraph can be used. With one set of gradiometer coils mounted at 45 degrees to the axis of the dewar, and by suitable tilting and rotating of the

dewar about the vertical axis, a single set of gradiometer coils would be capable of monitoring the three diagonal components of the ambient field if these measurements do not have to be made simultaneously.

If it is not required to measure both a field component and a gradient component during the same exercise, a further reduction in cost can be achieved. If this limitation is imposed, a single SQUID system and substrate block with multiple loops mounted on it can be used. Between cyclings to cryogenic temperatures, the loops on the substrate block can be connected together in series aiding, series opposition or selectively shorted out to obtain either a gradiometer or a magnetometer configuration. It is this configuration, that is, a system consisting of one dewar, one SQUID sensor (and associated electronics detection), one low temperature probe supporting a single substrate block on which is mounted several sets of coils which can be connected in several ways, that was selected as the most cost effective choice for a versatile magnetometer/gradiometer system for use in demonstrating the feasibility of using SQUID circuits in Naval surveillance and communication applications at low frequencies.

3.2 Design Goals

In the design of a combination magnetometer/gradiometer system, the first parameter that must be specified is the

inner diameter of the neck of the dewar container. This limits the dimension of any probe that can be inserted. The larger the ID of the neck, the more sensitive the instrument that can be used (see Figure 1) while, on the other hand, the larger the neck diameter, the greater is the thermal radiation down the neck and hence the larger the liquid helium boil-off rate. A compromise dimension for the dewar neck was set at 7.5 cm (3 inches) which would result in a modest helium boil off rate but still permit a coil system with a minimum detectable field change of about 10^{-14} tesla $Hz^{-1/2}$ to be inserted.

In Table I the various system parameters selected during the design are summarized along with the actual system characteristics achieved with the probe and dewar purchased from SHE Corp.[5] (To further economize, the room temperature portions of the SQUID system were not procured at this time as these parts are available from other systems presently within the Applied Superconductivity Section). A drawing of the magnetometer/gradiometer probe and the associated dewar is given in Figure 2 while a drawing of the coil substrate block, its orientation relative to the axis of the probe and the housing around the block is shown in Figure 3.

4.0 CONCLUSIONS

It has been demonstrated that a fairly simple but

versatile superconductive magnetometer/gradiometer probe system can be built which is capable of monitoring, at different times, either an arbitrary field component or a diagonal component of the gradient (that is, dH_i/dx_i) associated with a magnetic source.

In the near future, this instrument will be used to make noise measurements at various locations and in different magnetic environments.

TABLE I

SYSTEM SPECIFICATIONS

	Design Goals	Achieved
Magnetometer		
Minimum detectable Magnetic Field change (tesla (rms) $Hz^{-1/2}$)		
Most Sensitive Range	1×10^{-14}	1.06×10^{-14}
Reduced Sensitivity	1×10^{-13}	1.24×10^{-13}
Gradiometer		
Minimum detectable gradient change (tesla/cm $Hz^{-1/2}$)	0.5×10^{-15}	1.2×10^{-15}
Residual balance after repeated temperature cycling	100 ppm	50 ppm
Maximum balance achievable	1 ppm	0.5 ppm
Dewar		
Neck Diameter	7.5 cm	7.5 cm
Helium Boil-off rate with dewar vertical (liters/day)	2	1.2
Boil Off rate with dewar tilted 45 degrees to vertical (liters/day)	3	2.9

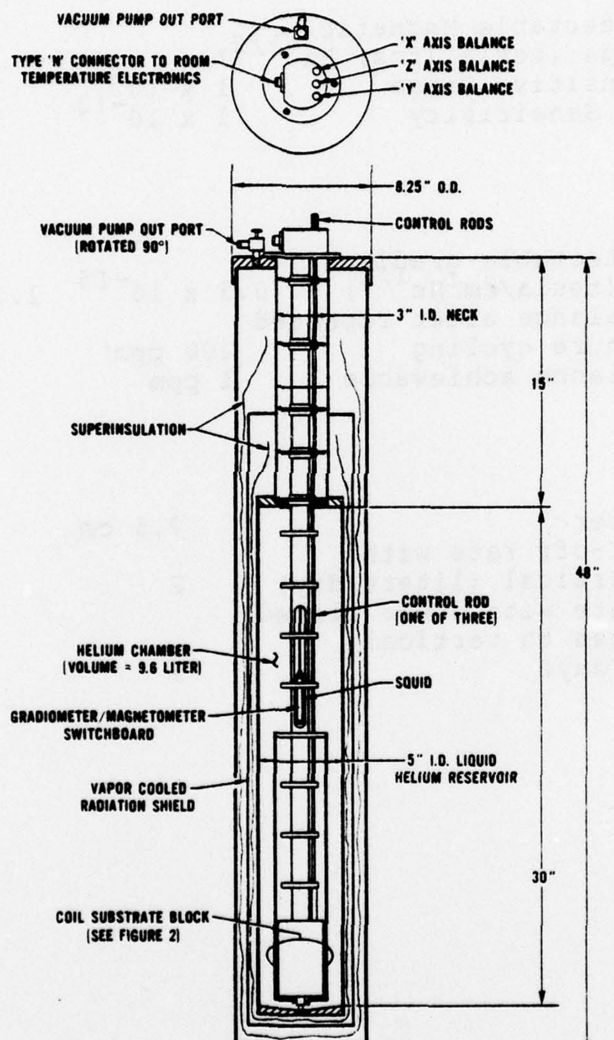

Fig. 2 — Drawing of magnetometer/gradiometer probe and dewar

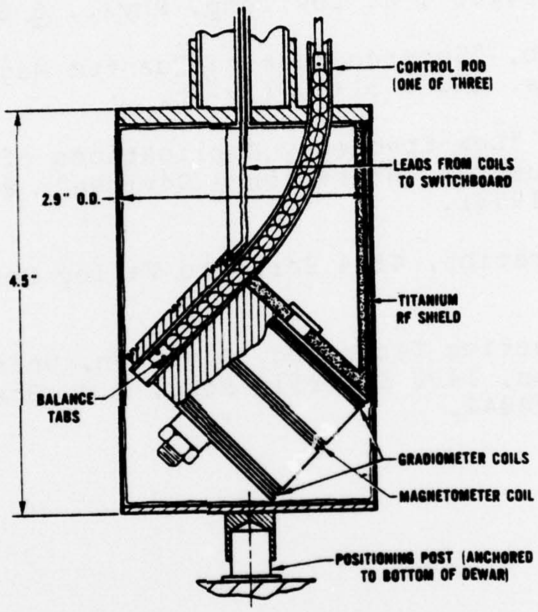

Fig. 3 — Detailed drawing of substrate block and substrate block housing

REFERENCES

1. A. H. Silver and J. E. Zimmerman, "Josephson Weak-Link Devices", Applied Superconductivity, Ed. by V. L. Newhouse (Academic Press, New York, 1975) Chapter I pp. 1-112.

2. R. P. Giffard, R. A. Webb and J. C. Wheatley, "Principles and Methods of Low-Frequency Electric and Magnetic Measurements Using an rf-Biased Point-Contact Superconducting Device", J. Low Temp. Phys., 6 533-610 (1972).

3. W. W. Webb, "Superconducting Quantum Magnetometers", IEEE Trans. MAG-8 51-60 (1972).

4. J. Clark, "Low-Frequency Applications of Superconducting Quantum Interference Devices", Proc. IEEE, 61 8-19 (1973).

5. SHE Corporation, 4174 Sorrento Valley Road, San Diego, CA 92121.

6. Superconducting Technology Division, United Scientific Corporation, 1400 Stierlin Road, P.O. Box 1389, Mountain View, CA 94042.